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Secure Communication Application of Josephson Tetrode in THz Region

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Abstract

We numerically demonstrate the generation of chaos in a four-terminal superconductive device made of five Jospehson weak-link junctions, Josephson Tetrode. We calculate the dynamics of electrical voltages across the junctions when one of the normal resistances in varied. We confirm the generation of chaos by using temporal waveforms, three-dimensional attractors and Lyapunov exponent of chaotic attractor. We numerically investigated the threshold voltage dependence and sampling time dependence of random bits. Jospehson Tetrode is a promising superconductive device applicable to secure communication in THz region.

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Keywords: Josephson Tetrode; Josephson device; supercondecting device; secure communication; phenomenological theories; THz electronics; superconducting optical, X-ray, and y-ray detectors (SIS,NIS, transition edge)

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1. Introduction

Since Brian David Josephson has discovered Josephson effect in 1962, there have been many studies about the application of Josephson junctions, the basic active elements of the superconductor electronics. Recently, Josephson junction devices have been used in many applications in many fields such as RSFQ (Rapid Single Flux Quantum), ultrahigh sensitive detectors and the celebrated SQUID (Superconducting Quantum Interference Device) that have been used to measure electronic and nuclear magnetism, field gradients for a wide variety of sources [1].

Josephson junctions as components in microwave receiver devices indeed reveal very interesting possibilities [2]. The oscillation frequencies of chaos in Josephson junction are potentially of thousands of gigahertz. Therefore, Josephson junction devices could be useful for ultrahigh speed chaotic generators for application in secure communications. There have been many studies on chaotic dynamics in Josephson junction devices. Lots of previous researches are based on analysis of the tunnel junction with the RCSJ (Resistively and Capacity Shunted Josephson junction) model. However, to obtain ultra fast oscillations at frequencies of thousands of gigahertz, it is better to use microbridge configurations of Josephson junctions instead of tunnel junctions, because the capacitance is negligible.

In order to generate ultrafast chaotic oscillation for the purpose of engineering applications of random signal generation, Josephson junction devices must have three conditions as mentioned follows:

- Small and simple device
- Autonomous systems which is do not need external modulation
- No capacitance

It is important for the Josephson junction devices to meet the requirements, but until now, Josephson junction devices that meet all the requirements have not been developed yet. Josephson Triode is one of the simplest Josephson junction devices that had been demonstrated. However, in Josephson triode, there is one dependent variable and only two variables are independent which could not satisfy the necessary conditions for generation of chaos that need three independent variables. Thus, we use Josephson tetrode, which has three independent variables.

In this paper, we numerically analyze the dynamics of the threshold voltage dependence and sampling time dependence of random bits.

2. Equivalent Model

Josephson Tetrode consists of four superconductive devices, which are referred as 1, 2, 3 and 4 respectively, and is connected with weak-link material. The equivalent circuit of Josephson Tetrode in Fig. 2 is described with five Josephson junctions and resistors. In the Josephson Tetrode, two of the junctions are series connected (1-2 and 2-3) and the other three junctions are parallel connected (1-4, 2-4 and 3-4). The capacitance of a junction is assumed to be negligible. Microbridge junctions may exhibit an inductive part that may lead to a phase shift between current and voltage. There may also be a substantial contribution to the junction inductance due to kinetic inductance. However, all these small inductive effects can be ignored and conventional RSJ model is used to describe the dynamics of the Josephson tetrode in this paper [3].

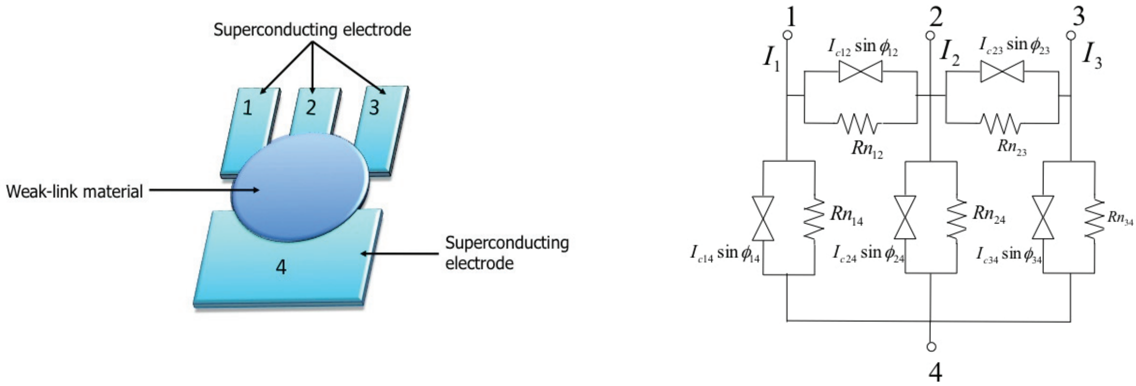

Fig. 1. (a) Schematic of Josephson Tetrode; (b) Equivalent circuit of the Josephson Tetrode

In the Josephson Tetrode, three independent differential equations is derived for the phase difference of wave functionsΦ_{12}, ϕ_{12},ϕ_{23} Φ_{23} and ϕ_{14} Φ_{14}. The other variances of ϕ_{24} $\Phi_{24}$and ϕ_{34} Φ_{34}can be described as dependent variances since it is assumed that magnetic flux in the loop of the Josephson junctions whose length is much smaller than the coherent length. Therefore, the sum of the phase differences of wave functions in one loop is zero.The dependent variances are derived as;

$$\phi_{24} = \phi_{14} - \phi_{12} \tag{1}$$

$$\phi_{34} = \phi_{14} - \phi_{12} - \phi_{23} \tag{2}$$

From the equivalent circuit, basic equations for dc drive current and that flowing through the junctions can be described as follows;

$$I_1 = I_{C14}\sin\phi_{14} + \frac{1}{Rn_{14}}\cdot\frac{\hbar}{2e}\cdot\frac{d\phi_{14}}{dt} + I_{C12}\sin\phi_{12} + \frac{1}{Rn_{12}}\cdot\frac{\hbar}{2e}\cdot\frac{d\phi_{12}}{dt} \tag{3}$$

$$I_2 = I_{C23}\sin\phi_{23} + \frac{1}{Rn_{23}}\cdot\frac{\hbar}{2e}\cdot\frac{d\phi_{23}}{dt} + I_{C24}\sin\left(\phi_{14} - \phi_{12}\right) + \frac{1}{Rn_{24}}\cdot\frac{\hbar}{2e}\cdot\frac{d\left(\phi_{14} - \phi_{12}\right)}{dt} \tag{4}$$
$$-I_{C12}\sin\phi_{12} + \frac{1}{Rn_{12}}\cdot\frac{\hbar}{2e}\cdot\frac{d\phi_{12}}{dt}$$

$$I_3 = I_{C34}\sin\left(\phi_{14} - \phi_{12} - \phi_{23}\right) + \frac{1}{Rn_{34}}\cdot\frac{\hbar}{2e}\cdot\frac{d\left(\phi_{14} - \phi_{12} - \phi_{23}\right)}{dt} + I_{C23}\sin\phi_{23} + \frac{1}{Rn_{23}}\cdot\frac{\hbar}{2e}\cdot\frac{d\phi_{23}}{dt} \tag{5}$$

Where ϕ_{ij} is the phase difference of wave function.

The fourth-order Runge-Kutta-Gill method is used to integrate and calculate the equations. The dynamics of the Josephson Tetrode is calculated with parameters as follows; Rn_{14} is variable, $Rn_{12} = 1.0\Omega, Rn_{23} = Rn_{24} = 10.0\Omega, Rn_{34} = 5.0\Omega, I_1 = 1.3mA, I_2 = 1.2mA$ and $I_3 = 1.1mA$.

In this paper, superconducting material in the tetrode is assumed to be made of $YBa_2Cu_3O_7$. Therefore the $I_C Rn$ product of all junctions is constant near the critical temperature T_C for microbridge junctions. In this paper, $I_C Rn$ is assumed to be $0.45mV$. So, frequency of each Josephson junction is described as follows;

$$f = \frac{2eI_C Rn}{h} = 2THz \tag{6}$$

Temporal waveforms of normalized voltages are numerically calculated when Rn_{14} is varied. The equations of temporal waveforms of the normalized voltages can be described as follows;

$$V_{12}(t) = \frac{d\phi_{12}}{dt}, V_{23}(t) = \frac{d\phi_{23}}{dt}, V_{14}(t) = \frac{d\phi_{14}}{dt} \tag{7}$$

3. Results and Discussion

Fig. 2 shows temporal waveforms of the three normalized voltages at different values of Rn_{14} . At $Rn_{14} = 0.8\Omega$ the temporal waveforms are in chaotic oscillation state. When the value of Rn_{14} is increased to 0.9Ω , the temporal waveforms become quasi-periodic oscillation. As shown in Fig. 3, we also calculate three-dimensional attractors in the phase space of the three normalized voltage. From Fig. 3, we can state that attractor of $Rn_{14} = 0.8\Omega$ is more chaotic than attractor of $Rn_{14} = 0.9\Omega$.

Fig. 4 shows threshold voltage Vth dependence of frequency 1 at 100000 data of normalized voltage of V_{23} . It shows that value of Vth for each sampling time does not have so much difference.

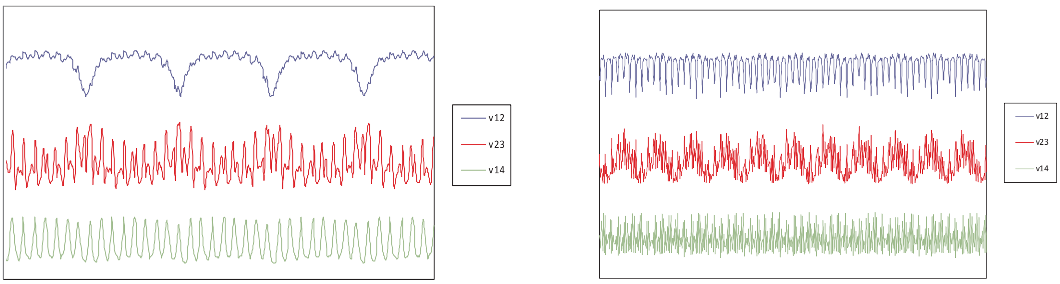

Fig. 2. Temporal waveforms of three normalized voltages at (a) $Rn_{14} = 0.8\Omega$; (b) $Rn_{14} = 0.9\Omega$

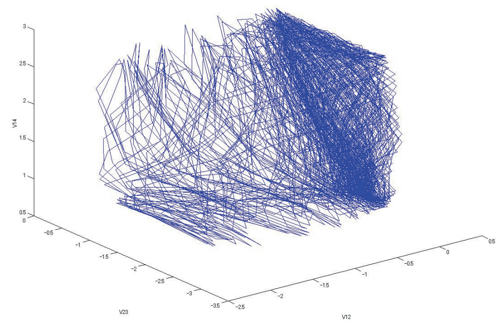

Fig. 3. 3D attractors at (a) $Rn_{14} = 0.8\Omega$; (b) $Rn_{14} = 0.9\Omega$

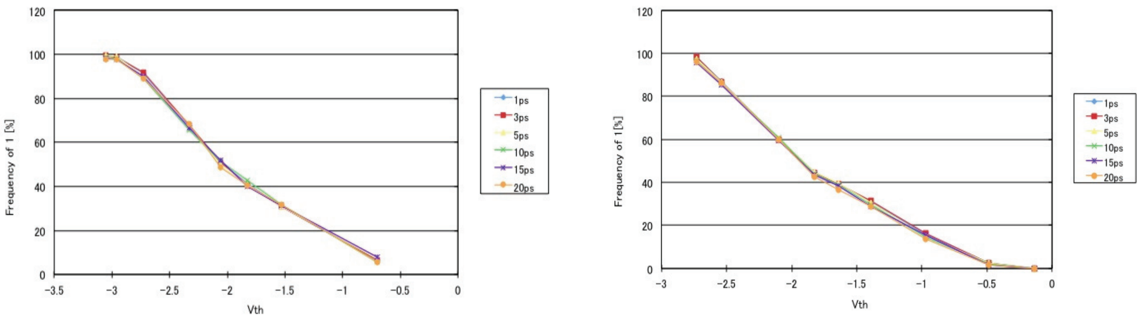

Fig. 4. Threshold voltages of Vth dependence of frequency of 1 at (a) $Rn_{14} = 0.8\Omega$; (b) $Rn_{14} = 0.9\Omega$

Table 1 shows the relation between sampling time and normalized threshold voltage. We try to figure any difference that cohesive between each sampling time. We set the frequency of 1 as 50% and as we can see above, the value of normalized threshold voltage for each sampling time is almost the same to another and do not increase nor decrease cohesively as the value of sampling time increase.

Table 1. Sampling time and threshold voltage

Sampling time [ps]	Normalized threshold voltage [Vth]	Frequency of 1 [%]
1	-2.045	50
3	-2.045	50.06
5	-2.06	50
10	-2.039	50
15	-2.035	50
20	-2.06	50.3

4. Conclusion

We confirmed the generations of chaos in Josephson Tetrode by using the temporal waveforms and 3D attractors. It is obvious that the value of normal resistance gives big impact to the oscillation. We clarify that the mechanism of the generation of chaos is a nonlinear frequency mixing among three independent voltages across the junction.

From the waveforms of Josephson Tetrode, we try to figure out the pseudo random number by optimizing the threshold voltages and the sampling time. From the results, we find that sampling time does not affect much the value of threshold voltage.

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